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"Basic Physics of Tokamak Transport"
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I. Introduction

The goal of this grant has been to study the basic physics of various sources of anomalous transport in tokamaks. Anomalous transport in tokamaks continues to be one of the major problems in magnetic fusion research. As a tokamak is not a physics device by design, direct experimental observation and identification of the instabilities responsible for transport, as well as physics studies of the transport in tokamaks, have been difficult and of limited value.

It is noted that direct experimental observation, identification and physics study of microinstabilities including ITG, ETG, and trapped electron/ion modes in tokamaks has been very difficult and nearly impossible. The primary reasons are co-existence of many instabilities, their broadband fluctuation spectra, lack of flexibility for parameter scans and absence of good local diagnostics. This has motivated us to study the suspected tokamak instabilities and their transport consequences in a simpler, steady state Columbia Linear Machine (CLM) with collisionless plasma and the flexibility of wide parameter variations.

Earlier work as part of this grant was focused on both ITG turbulence, widely believed to be a primary source of ion thermal transport in tokamaks, and the effects of isotope scaling on transport levels. Prior work from our research team has produced and definitively identified both the slab and toroidal branches of this instability and determined the physics criteria for their existence. All the experimentally observed linear physics corroborate well with theoretical predictions. However, one of the large areas of research dealt with turbulent transport results that indicate some significant differences between our experimental results and most theoretical predictions.

Latter years of this proposal were focused on anomalous electron transport with a special focus on ETG. There are several advanced tokamak scenarios with internal transport barriers (ITB), when the ion transport is reduced to neoclassical values by combined mechanisms of **E**x**B** and diamagnetic flow shear suppression of the ion temperature gradient (ITG) instabilities. However, even when the ion transport is strongly suppressed, the electron transport remains highly anomalous. The most plausible physics scenario for the anomalous electron transport is based on electron temperature gradient (ETG) instabilities. This instability is an electron analog of and nearly isomorphic to the ITG instability, which we had studied before extensively. However, this isomorphism is broken nonlinearly. It is noted that as the typical ETG mode growth rates are larger (in contrast to ITG modes) than **E**x**B** shearing rates in usual tokamaks, the flow shear suppression of ETG modes is highly unlikely. This motivated a broader range of investigations of other physics scenarios of nonlinear saturation and transport scaling of ETG modes.

II. Experimental Setup Using the Columbia Linear Machine

The layout of CLM is shown in Fig. 1. The plasma is produced in the source region by a hot-cathode E||B dc discharge (I_{dis}=80mA) in hydrogen ($P_s \cong 5\times10^{-4}$Torr). The plasma flows from the source region through a differentially pumped transition region to the experimental cell ($P_c \cong 5\times10^{-7}$Torr) where the plasma terminates on a conducting endplate. The rf heating meshes located in the transition region, effectively heat the core of the plasma. The typical parameters under normal operating condition with rf heating are: ion density n ~ 5×10^8-5×10^9cm^{-3}, neutral pressure in cell region $P_c \cong 5\times10^{-7}$ Torr, electron temperature T_c~6-10eV, perpendicular ion temperature $T_{i\perp}$~5eV, parallel ion temperature $T_{i||}$~5-15eV, magnetic field (experimental cell) B≅1kG, plasma cell length L ~ 80-160cm, plasma column radius r_p ~ 3cm, mirror ratio ~ 1-3 and mirror cell length ~ 50-80cm. Thus CLM has greatly expanded the parameter space accessible to the usual linear devices (eg. Q-machine, double plasma device, etc.) by achieving a wide range of collisionalities of both electrons and ions. Furthermore, its flexibility in wide range of variation of all the critical plasma parameters makes it ideally suited for scaling studies in basic plasma physics issues like transport.

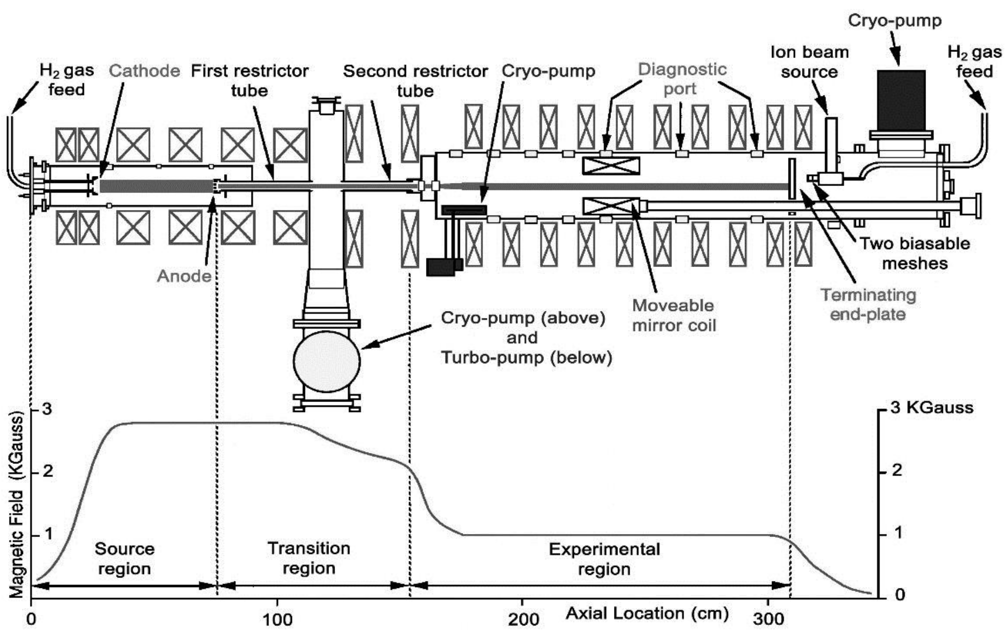

Fig. 1. Columbia Linear Machine.

All the diagnostics in CLM are performed via electrostatic probes and are local. The parallel and transverse ion temperatures are measured with gridded ion energy analyzer (IEA). Rectangular Langmuir probes are used to obtain electron temperature, ion saturation current and to detect density fluctuations. The d.c. plasma potential is measured by an emissive probe and the plasma potential fluctuation by a capacitive probe. The ion temperature fluctuations have been measured by a novel a.c. ion energy analyzer exploiting feedback diagnostics. The electron temperature fluctuations are measured by a novel high-frequency triple probe using a capacitive probe and capacitive coupling to the potential fluctuations of a double probe. All probes and analyzers are fixed at axial positions but can be moved radially to obtain profiles of the various plasma parameters.

III. Summary of Accomplishments.

The results of this research are best summarized by the full list of peer reviewed publications appended to the end of this report. However, we will highlight a few particularly unique and strong accomplishments over the years:

i. A New Paradigm of Plasma Transport With Inverse Gyro-Bohm Scaling:

Most tokamak experimental results indicate dependence of the ion thermal conductivity on the isotopic mass close to $\chi_\perp \sim A_i^{-0.5}$, i.e. inverse gyro-Bohm in mass scaling. This is in stark contradiction to most present theoretical models predicting Bohm (A_i^0) or gyro-Bohm ($A_i^{0.5}$) scaling. A basic physics experiment on the anomalous ion thermal conduction due to ion temperature gradient instabilities in two different gases (hydrogen and deuterium) closely confirms the tokamak results.

We conducted a series of experiments designed to explore the physical basis of this scaling, which appears to lead to a new model for this scaling based on three-wave coupling of two ion temperature gradient radial harmonics and an ion acoustic (IA) wave. The resulting isotopic scaling of transport is ~ $A_i^{-0.5}$, dictated primarily by the IA damping. This basic physics is deemed to be extrapolatable to tokamaks resolving the paradox and is tantamount to a new paradigm for plasma turbulent transport.

ii. Controlled Production and Identification of Zonal Flows:

We conducted a basic physics experimental study of zonal flows associated with ITG (ion temperature gradient) drift modes in the Columbia Linear Machine. The difficult problem of detection of zonal flows was solved via a novel diagnostic using the paradigm of FM (frequency modulation) in radio transmission. Using this and Discrete Short Time Fourier transform, we find a power spectrum peak at the ITG ('carrier') frequency of *~120kHz* and FM sidebands at a frequency of *~2kHz*, which has all the signatures of a zonal flow.

iii. Feedback Assisted Experimental Studies of Zonal Flow Saturation and Scalings

Our experiments were able to reveal zonal flows (ZF) scalings over a wide parameter ranges. The scaling of ZF amplitude with that of ion temperature gradient mode (ITG) via increasing ITG drive through increasing RF heating ($\sim\eta_i$) revealed an expected monotonic behavior. More selective studies via feedback (stabilizing/destabilizing) revealed the unique complementary roles of IA (ion acoustic) and ZF shearing in the saturation of ITG modes. Experimental variation of total ion collisionality over nearly half an order of magnitude, revealed no change in the amplitude of ZF, contrary to prior theoretical understanding.

iv. Controlled Production, Identification and Study of ETG Modes

The electron temperature gradient (ETG) mode, which is believed to be one of the strongest candidates for the anomalous electron energy transport in plasma physics, is notoriously difficult to detect in experiments because of its high frequency (order of *MHz*) and short wave length characterized by the parameter $k_\perp \rho_e \leq 1$. Using a DC bias heating scheme of the core plasma, we were able to produce a sufficiently strong electron temperature gradient for exciting ETG modes in Columbia Linear Machine (CLM), one of the earliest experiments to do so in a controlled fashion. A high frequency mode thus produced has all the relevant signatures of ETG modes: $\omega/2\pi \sim 2.3 MHz$, $m \sim 14\text{-}16$ and $k_\parallel \sim 0.01 cm^{-1}$. The scaling of its fluctuation level with the temperature gradient scale length and the radial structure are found to be roughly consistent with theoretical expectations. Our later work also included studies into the saturation mechanisms for ETG turbulence.

IV. Doctoral Students' Thesis Supported Under Grant Funding:

Four students have completed their Ph.D's under sponsorship of this grant, with a fifth student expected to complete their PhD in the coming year:

Johannes. Chiu (E.E.), ~ Graduated 2000

Zhipeng Sun (EE), ~ Graduated 2008

Xiao Wei (APAM) ~ Graduated 2011

Erinc Tokluoglu (EE) ~ Graduated 2014

Abed Balbaky (EE) ~ est. Graduation 2015

Additionally many undergraduate students have had a chance to contribute and participate in the research supported by this grant over the years, and the research supported by this grant has been a part of several collaborations with other research groups at PPPL, UT Austin, Univ. of Wisconsin, and internationally with the Univ. of Aix-Marseille France.

V. Concluding Remarks

On the whole we consider this grant to have been a resounding success. We have consistently fulfilled our goals and have produced several cutting edge discoveries and experimental verifications of the basic physics behavior of plasma. This research has also had an incalculable positive effect on the research community as a whole and the various graduate and undergraduate students who have had a chance to participate over the years. It is clear that there will always be more work to be done, and CLM itself will hopefully continue to do good work under another grant at some point in the near future. OFE of DOE should be highly lauded for their productive support over the years.

VI. Peer Reviewed Publications Made Under the Grant

1. "Experimental determination of attractor dimension of ExB turbulence", J. S. Chiu and A. K. Sen, *Phys.Plasmas*, **7**, 4492 (2000).

2. "Optimal control of tokamak resistive wall modes in the presence of noise", A. K. Sen, M.Nagashima, and R.W.Longman, *Phys.Plasmas*, **7**, 4492 (2000).

3. "A basic experiment on isotope scaling of transport", T. Bose and A. K. Sen, *Phys.Plasmas*, **8**, 4690 (2001).

4. "A hybrid ion temperature gradient and Kelvin–Helmholtz instability", A. K. Sen,V.Reva, K.Avinash, *Phys.Plasmas*, **8**, 4772 (2001).

5. "Experimental Studies of Isotope Scaling of Ion Thermal Transport", V.Sokolov and A.K.Sen, *Phys.Rev.Lett.*,**89**,095001 (2002).

6. "Experimental Investigation of Isotope Scaling of Anomalous Ion Thermal Transport", V. Sokolov and A. K. Sen, *Phys. Plasmas,* **10**, 3174 (2003).

7. "New Paradigm for the Isotope Scaling of plasma Transport Paradox", V.Sokolov and A.K.Sen, *Phys. Rev. Lett*, **92**, 165002 (2004).

8. "Feedback Control of Kink and Tearing Modes via Novel ECH Modulation", A. K. Sen, *Plasma Phys.Control.Fusion,* **46**, L41 (2004).

9. "A New Paradigm for Plasma Transport", V.Sokolov and A.K.Sen, Nucl. Fusion, **45**, 439 (2005).

10. "Experimental Study of Isotope Scaling of Plasma transport in Axisymmetric Magnetic Field", V.Sokolov and A.K.Sen, *Trans. Fusion Science & Technology*, **47**, 1T, 270 (2005).

11. "Observation and Identification of Zonal Flows in a Basic Physics Experiment", V.Sokolov, X.Wei, A.K.Sen and K.Avinash, *Plasma Physics and Controlled Fusion,* **48**, S111 (2006).

12. “Adaptive Optimal Stochastic State Feedback Control of Resistive Wall Modes in Tokamaks”, Z.Sun, A.K.Sen, R.Longman, Phys. Plasmas, 13, 012512 (2006).
13. “A New Paradigm for Plasma Transport and Zonal Flows”, A.K.Sen, V.Sokolov, and X.Wei, *Phys. Plasmas*, **13**, 055905 (2006).
14. “Adaptive Stochastic Output Feedback Control of Resistive Wall Modes in Tokamaks”, Z.Sun, A.K.Sen, R.Longman, Phys. Plasmas 13, 092508 (2006).
15. “Observation and Identification of Zonal Flows in a Basic Plasma Physics Experiment”,V.Sokolov, X.Wei and A.K.Sen, *Phys. Plasmas*, **14**, 055906 (2007).
16. “A New Paradigm for Radial Ion Plasma Transport in Axisymmetric Magnetic Field”, V.Sokolov and A.K.Sen, *Fusion Science and Technology*, **51**,100 (2007).
17. “Feedback Assisted Experimental Studies of Zonal-Flow saturation and Scaling”, V.Sokolov, X.Wei and A.K.Sen, *Phys.Rev.Lett.*,**104**, 025002 (2010).
18. “Experimental Production and Identification of Electron Temperature Gradient modes”, X.Wei, V.Sokolov and A.K.Sen, *Phys.Plasmas*, **17**, 042108 (2010).
19. “Experimental Observation of Zonal Flow and Its Scalings in Axisymmetric Magnetic Field”, V.Sokolov, X.Wei and A.K.Sen, *Fusion Science and Technology*, **59**,N1T,154 (2011).
20. “Feedback Control of Major Disruptions in International Thermonuclear Experimental Reactor”, A. K. Sen, *Phys.Plasmas*, **18**, 082502 (2011).
21. “Measurements of Electron Thermal Transport Due to ETG Modes in a Basic Experiment”, V.Sokolov and A.K.Sen, *Phys.Rev.Lett.*,**107**, 155001 (2011).
22. “Validation of electron temperature gradient turbulence in the Columbia Linear Machine”, X. R. Fu, W. Horton, Y. Xiao, Z. Lin, A. K. Sen, and V. Sokolov, *Phys.Plasmas*, **19**, 032303 (2012).
23. “Ion energy analyzer for measurement of ion turbulent transport”, V.Sokolov and A.K.Sen, *Rev. Sci. Instrum.* **83**, 103503 (2012).
24. “Non-Linear Saturation Mechanism of Electron Temperature Gradient Modes”, E.K. Tokluoglu, V. Sokolov, and A.K. Sen, *Phys. Plasmas*, **19,** 102306 (2012)

In addition to these peer reviewed publications, there are approximately 20 papers at various APS, IAEA, and other physics conferences, as well as several invited talks, at national and international forums.